Spectra] Calibration Requirement for Earth-looking Imaging Spectrometers in the Solar Reflected Spectrum

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ABSTRACT

Earth-looking imaging spectrometers operating in the solar reflected spectrum, measure spectra of the total upwelling radiance for each spatial element in an image. These measurements are used to derive physical parameters of the Earth's surface and atmosphere based on the energy, molecular absorption, and constituent scattering characteristics expressed in the spectra over the region of the image. To derive these parameters, the measured spectra must be spectrally, radiometrically and spatially calibrated to a specified accuracy. To determine the requirement for spectral calibration accuracy, a sensitivity analysis has been completed examining the calibration sensitivity for imaging spectrometers with spectral channel response functions of 5 nm, 10 nm, and 20 nm width in the solar reflected spectrum (400 nm to 2500 nm). The ubiquitous presence of numerous, strong, narrow atmospheric and solar absorptions in the upwelling radiance in conjunction with the contiguous narrow spectral channels of an imaging spectrometer are shown to drive the spectral calibration requirement in this spectral region. This analysis shows that a spectral calibration accuracy approaching one percent of the full width at half maximum throughput of the spectral response, function is required to eliminate significant, spectrally distinct errors in the imaging spectrometer measured upwelling radiance.

KEYWORDS: imaging Spectrometer, Spectral Calibration

1.0 INTRODUCTION

Airborne and spaceborne imaging spectrometers operating in the solar reflected spectrum are being developed to pursue scientific research and applications in the Earth's land, water, and atmosphere environments. These instruments typically measure spectra with more than 100 contiguous spectral channels in some or all of the region between 400 nm and 2500 nm. Response functions of the spectral channels in these instruments have full widths at half maximum (FWHM) throughput ranging from 5 nm to 20 nm. Spectra are measured for each spatial resolution element of an image of the Earth.

Spectra measured by an imaging spectrometer result from the exact convolution of the upwelling spectral radiance through the instrument spectral response functions. For all Earth-looking imaging spectrometers, the upwelling spectral radiance contains numerous, strong, narrow absorption from the solar source and Earth's atmosphere. To model this radiance, the MODTRAN radiative transfer code, [1,2] was used to generate a nominal upwelling radiance spectrum at high spectral resolution. To simulate a range of imaging spectrometers, sets of contiguous spectral channels with Gaussian spectral response functions were generated from 400 nm to 2500 nm with FWHM and wavelength sampling intervals at 5 nm, 10 nm, and 20 nm. Convolution of the MODTRAN radiance with the imaging spectrometer spectral response function simulates the imaging spectrometer measured radiance. To assess the requirement for spectral calibration accuracy, uncertainty in the knowledge of the spectral calibration was introduced and the resulting error in measured spectral radiance was calculated. Errors in measured radiance as a function of spectral calibration error are presented and analyzed. This work is based on investigations of the in-flight spectral calibration of NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). [3,4,5,6]

2.0 ME TI1OD

An upwelling radiance spectrum at the top of the atmosphere was modeled at 1.0 nm spectral resolution with MODTRAN (Fig. 1). MODTRAN was constrained with a 45 degree solar illumination angle, 0.25 reflectance surface at sea level and the standard mid-latitude summer atmospheric model. This spectrum is dominated by numerous, strong and narrow atmospheric and solar absorption. While this model spectrum was generated for a single case, the solar and atmospheric absorption expressed in this spectrum are present over the full range of surface reflectances and observation geometries encountered by Earth-looking imaging spectrometers. For example, even for low altitude airborne imaging spectrometers, these absorption are present in the radiance measured as a consequence of the downwelling path through the atmosphere. This modeled spectrum forms the basis for the spectral calibration sensitivity analysis and requirement determination.

For each spectral channel of an imaging spectrometer, the measured radiance L_i is the integral of the product of the spectral response function $f(\lambda_i - \lambda)$ and the upwelling spectral radiance $L(\lambda)$ at each wavelength $d\lambda$ (Equation 1).

$$L_i = \int f(\lambda_i - \lambda)^* L(\lambda) d\lambda \qquad (1)$$

The spectral position and shape of each imaging spectrometer channel determi ncs the radiance measured from the upwelling spectral radiance source. To simulate the radiance measured by an imaging spectrometer, the upwelling spectral radiance is convolved with the spectral response functions (Fig. 2). To investigate the sensitivity of the measured radiance to the spectral calibration, errors in the spectral response functions were introduced. Error in the calibration of spectral channel position was simulated through a systematic shift across the spectral range. Error in spectral channel shape was simulated through systematic broadening of the channel FWHM.

The effect of these errors was assessed as the percentage difference in measured radiance with and without the introduced spectral calibration error.

3.0 RESULTS

The first case investigated was for an imaging spectrometer operating from 400 nrn to 2500 nm with 10 nrn contiguous channels. Spectral calibration errors were introduced as shifts in the spectral response functions of 1,0 nm, 0.5 nm and 0.1 nm. These correspond to 10, 5, and 1 percent calibration errors with respect to the 10 nm FWHM of the spectral response functions. The percentage difference in the measured radiance with and without the spectral calibration position errors was calculated across the spectrum (Fig. 3a). Strong, spectrally distinct errors in measured radiance occur throughout the spectral range as a consequence of the errors in calibration of spectral channel positions. This sensitivity result from the convolution of the narrow imaging spectrometer channels with the upwelling radiance that contains narrow, strong atmospheric and solar absorption. For example; at 940 nrn, an error of 1.0 nm or 10 percent in channel position resulted in a 15 percent error in measured radiance. A 0.5 nm and 0.1 nrn error in spectral calibration leads to an 8 percent and 1.5 percent error in measured radiance respectively. In regions of spectrum with strong, narrow absorption, errors in spectral position calibration of a given percentage lead too comparable or greater errors in the measured radiance.

Sensitivity of channel shape to calibration was investigated for errors in FWHM of 1.0 nrn, 0.5 nm, and 0.1 nm (Fig. 3b). As with channel position, errors in the calibration of channel shape introduce spectrally distinct errors in the measured radiance. At 1120 nrn, errors in channel width of 1.0 nm, 0.5 nrn, and 0.1 nm result in radiance errors of 11.3, 5.6, and 1.1 percent, respectively.

To extend this analysis to a broader range of Earth-1 ooking imaging spectrometers, sensitivity analyses were completed for 5 nm and 20 nm spectral response function instruments. For a 5 nm imaging spectrometer, the percentage error in measured radiance for 0.5 nm, 0.1 nm, and 0,05 nm errors for both channel position and channel FWHM were calculated (Fig. 4a and 4b). Equivalent anal yses were performed for an imaging spectrometer with 20 nm spectral response functions for spectral calibration errors of 2.0 nm, 1 nm, and 0.2 nm errors for both channel position and channel FWHM (Fig. 5a and Fig. 5b). As with the 10 nm imaging spectrometer, these analyses show that significant, spectrally distinct errors in the measured radiance are induced by spectral calibration errors where solar and atmospheric absorption are present.

The radiance measured by imaging spectrometers with 5 nm, 10 nm, and 20 nm channels is sensitive to the accuracy of the calibration of the spectral channel position and channel shape. Radiance errors from errors in calibration of channel shape arc less dominant, but clearly expressed, relative to radiance errors caused by errors in calibration of channel position. Spectral calibration errors of 5 and 10 percent of the FWHM in channel position or channel shape cause radiance errors in the measured radiance that resemble spectral absorption and emission features. only when the spectral calibration accuracy approaches 1 percent of the FWHM are the spectrally distinct errors in the measured radiance largely suppressed,

4.0 **Discussion**

A single modeled radiance source spectrum with a uniform 0.25 reflectance surface, standard atmosphere and nominal observation geometry was used for these analyses. Radiance measured by current and planned imaging spectrometers spans a range of atmosphere, surface and observation conditions. The spectral calibration sensitivity results derived in this paper are generally applicable, because the source of the spectral calibration sensitivity are the solar and atmospheric absorptions present i n every Earth-looking measurement. The strengths of the atmospheric absorption will vary with atmospheric composition and observation geometry, but the absorption will always be present. inclusion of surface spectral reflectance in the reflected radiance, with additional spectral absorption, will only increase the sensitivity to spectral calibration accuracy in the spectral regions of the absorption.

These analyses were performed simulating calibration errors as a shift in position and broadening of the FWHM of the imaging spectrometer spectral response functions. These types of errors are consistent with alignment sensitivities of imaging spectrometer designs where detector arrays are mounted in the focal planes of imaging systems that contain dispersive optics. More complicated forms of spectral calibration error will induce equivalent or greater effects based on the sow-cc of the spectral calibration sensitivity. This source is the interplay of the narrow spectral channels of the Earth-looking imaging spectrometer and the narrow solar and atmospheric absorption of the upwelling spectral radiance.

Results presented arc for imaging spectrometers with equal spectral sampling and spectral response functions across the solar reflected spectrum. For example, 10 nm sampling and 10 nm FWHM. Because the sensitivity to spectral calibration results from the exact convolution of the upwelling radiance for each channel, an imaging spectrometer with 5 nm sampling and 1() nm FWHM shows the same sensitivity.

Spectral calibration sensitivity of imaging spectrometers with channels narrower than 5 nrn and wider than 20 nm can be predicted based upon the results presented in this paper. Channels narrower than 5 nm will be increasing y sensitive to the fine solar and atm ospheric spectral absorption.s contained in the Earth's upwelling radiance spectrum. This trend of increasing sensitivity to spectral calibration with narrower spectral resolution is shown in the change from 1() nm channels to 5 nrn channels. The converse trend in spectral calibration sensitivity is apparent from 10 rim to 20 nm channel. Except in the regions of the major water vapor absorption, channels coarser than 20 nm will show reduced spectral calibration sensitivity as the spectral resolution becomes significantly larger than the solar and atmospheric spectral absorption present in the upwelling radiance.

1 n addition to imaging spectrometers, remote sensing instruments with discrete narrow spectral bands arc being developed for rc.search and applications in the land, water and atmosphere environments. The spectral calibration sensitivity of these instruments can be assessed with the results presented in this paper based upon the spectral location and spectral response function FWHM of the discrete bands in these Earth-looking instruments.

5.0 Conclusion

The accuracy of radiance measured by imaging spectrometers in the solar reflected spectrum is strongly sensitive to spectral calibration. These analyses demonstrate that the ubiquitous, strong, **narrow** solar and atmospheric absorption present in the Earth's upwelling spectral radiance drive the requirement for spectral calibration of imaging spectrometers in the solar reflected spectrum (400 nm to 2500 rim). Calibration errors of both spectral channel position and spectral channel FWHM have been investigated and shown to cause strong, spectrally distinct errors in the imaging spectrometer measured radiance. in the presence of major atmospheric absorption, spectral calibration errors arc amplified as errors in the measured radiance. Errors introduced in the measured radiance from spectral calibration errors both mimic and distort the spectral characteristics of the atmosphere, water and land environments that arc the basis for imaging spectrometer research and applications. A spectral calibration accuracy approaching 1 percent of the spectra] response function FWHM is required to deliver measured radiance free of significant, spectrally distinct errors.

Acknowledgments

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Figure Captions

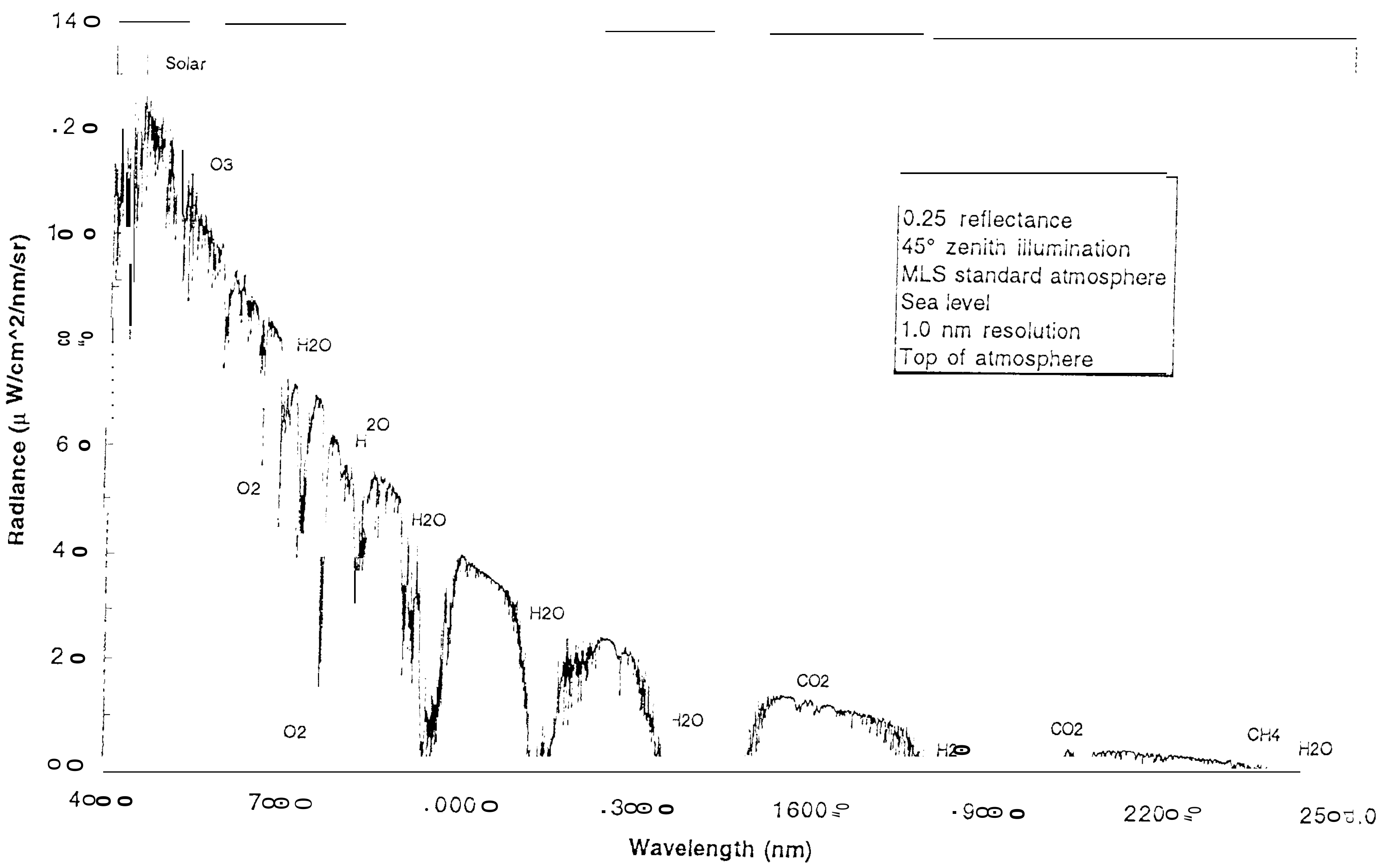
Fig. 1. Upwelling spectral radiance modeled At 1.0 nm spectral resolution with the MODTRAN radiative transfer code. Numerous, strong and narrow solar and atmospheric absorption arc expressed across the spectrum.

Fig. 2. Convolution of the modeled high resolution upwelling spectral radiance with the spectral response functions of an Earth-looking imaging spectrometer with 10 nm channels. The spectral range from 650 nm to 1350 nm is shown,

Fig. 3. (a) Measured radiance errors for spectra with 1.0 nm, 0.5 nm, and 0.1 nm errors in the calibration of imaging spectrometer spectral channel position. (b) Measured radiance errors resulting from spectral calibration errors of 1.0 nm, 0.5 nm, and 0.1 nm in channel FWHM.

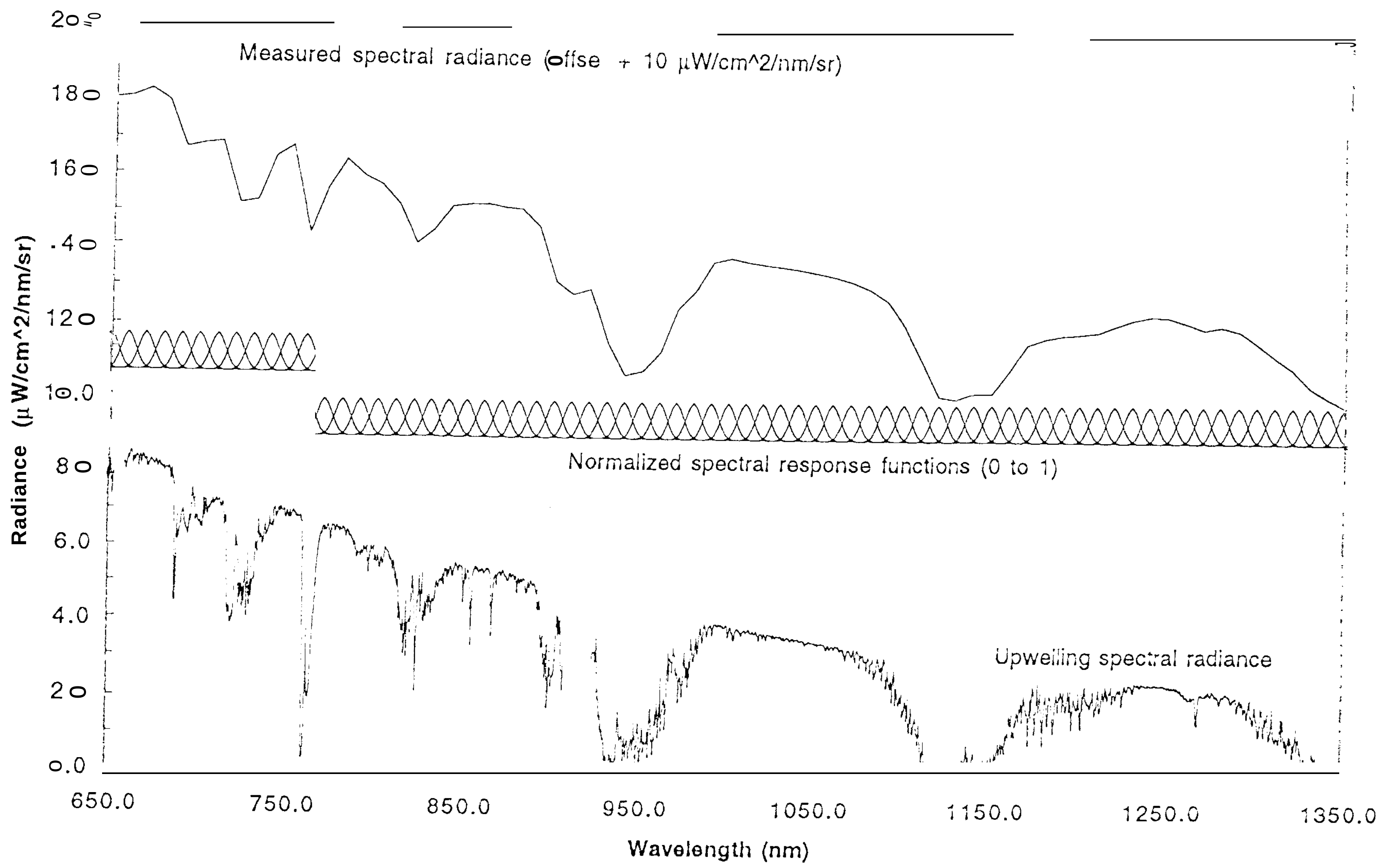
Fig. 4. Radiance errors for an imaging spectrometer with 5 nm channels resulting from (a) errors in calibration of spectral position and (b) errors in calibration of channel FWHM.

Fig. 5. Radiance errors for an imaging spectrometer with 20 nm channels resulting from (a) errors in calibration of spectral position and (b) errors in calibration of channel FWHM.



Radiance (μ W/cm^2/nm/sr)
Wavelength (nm)
Solar
O3
H2O
O2
H2O
O2
H2O
H2O
CO2
CO2
CH4
0.25 reflectance
45° zenith illumination
MLS standard atmosphere
Sea level
1.0 nm resolution
Top of atmosphere

Fig 1



Measured spectral radiance (offse + 10 µW/cm^2/nm/sr)
Normalized spectral response functions (0 to 1)
Upwelling spectral radiance
Radiance (µW/cm^2/nm/sr)
Wavelength (nm)
650.0
750.0
850.0
950.0
1050.0
1150.0
1250.0
1350.0

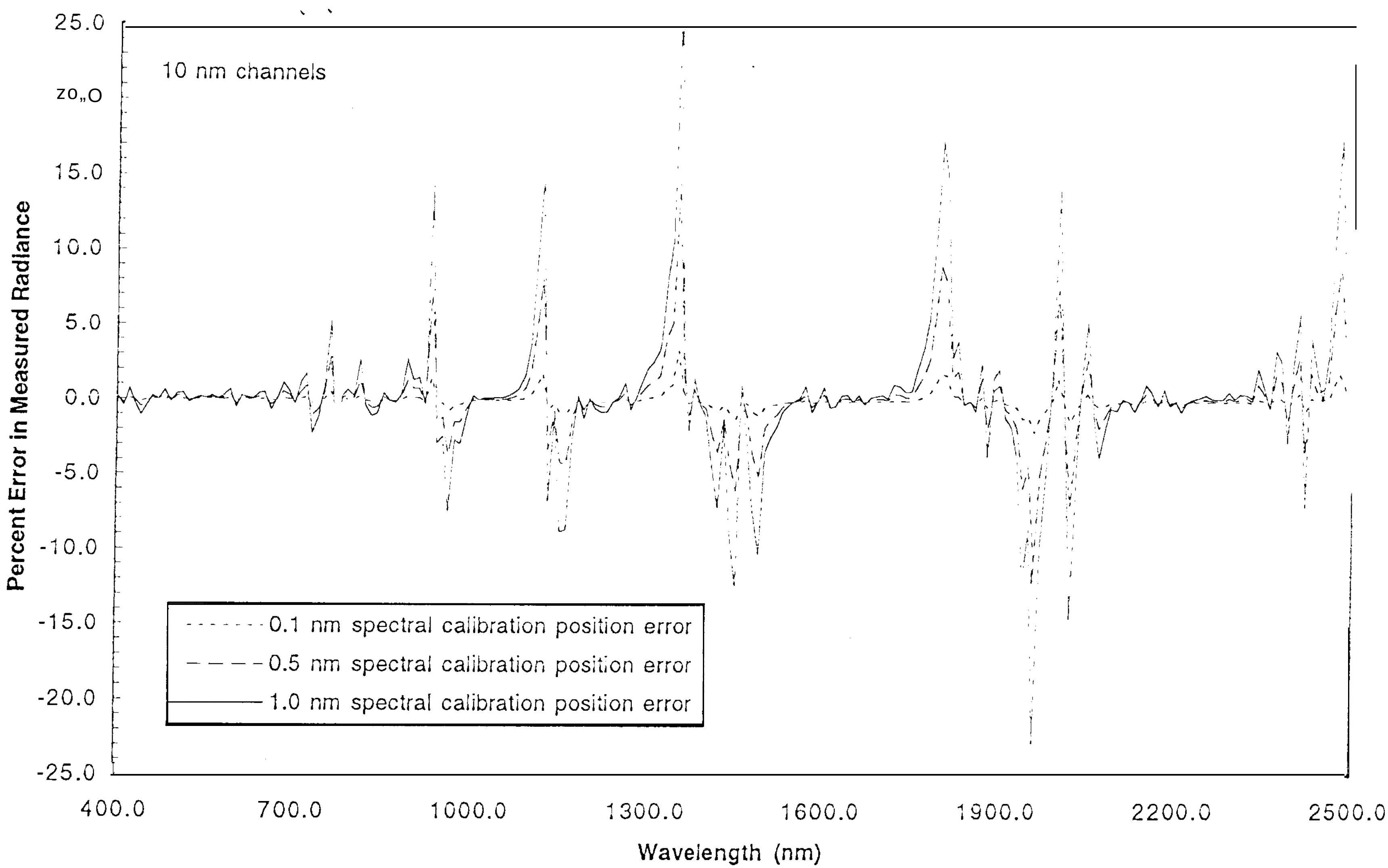
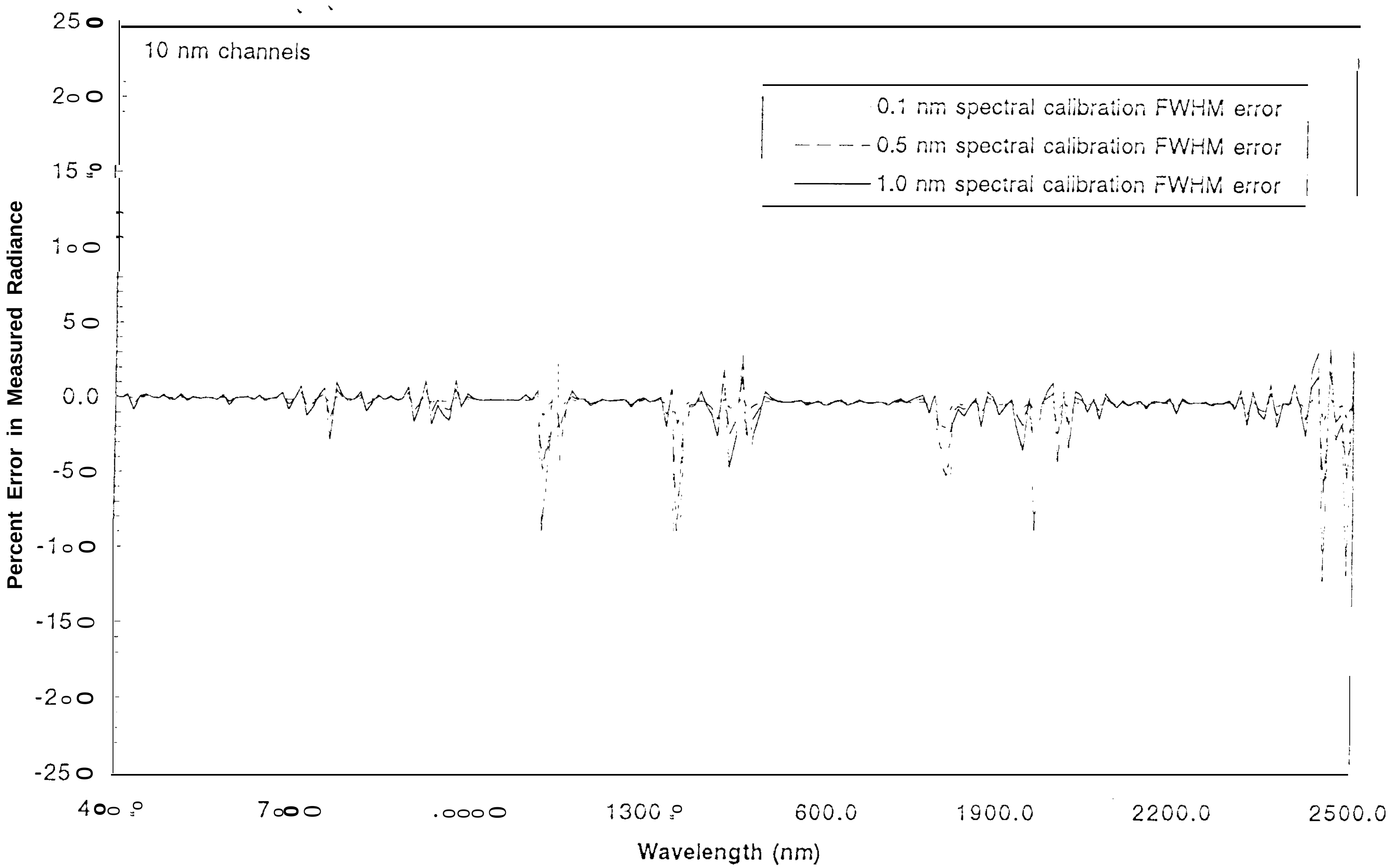

10 nm channels
Percent Error in Measured Radiance
25.0
zo„O
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
400.0
700.0
1000.0
1300.0
1600.0
1900.0
2200.0
2500.0
Wavelength (nm)
0.1 nm spectral calibration position error
0.5 nm spectral calibration position error
1.0 nm spectral calibration position error

Fig 2



Percent Error in Measured Radiance
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
10 nm channels
0.1 nm spectral calibration FWHM error
0.5 nm spectral calibration FWHM error
1.0 nm spectral calibration FWHM error
400.0
700.0
1000.0
1300.0
1600.0
1900.0
2200.0
2500.0
Wavelength (nm)

93

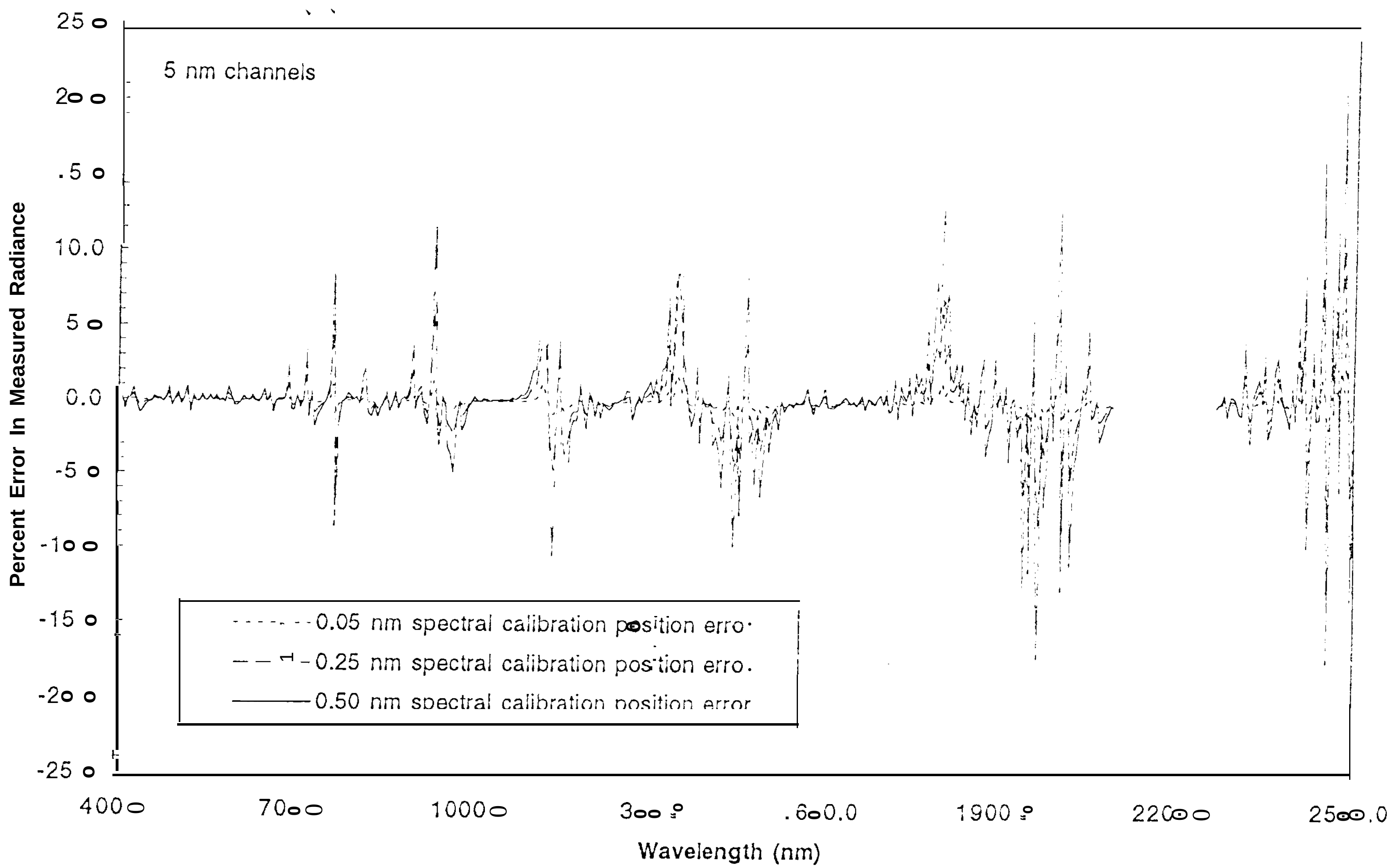
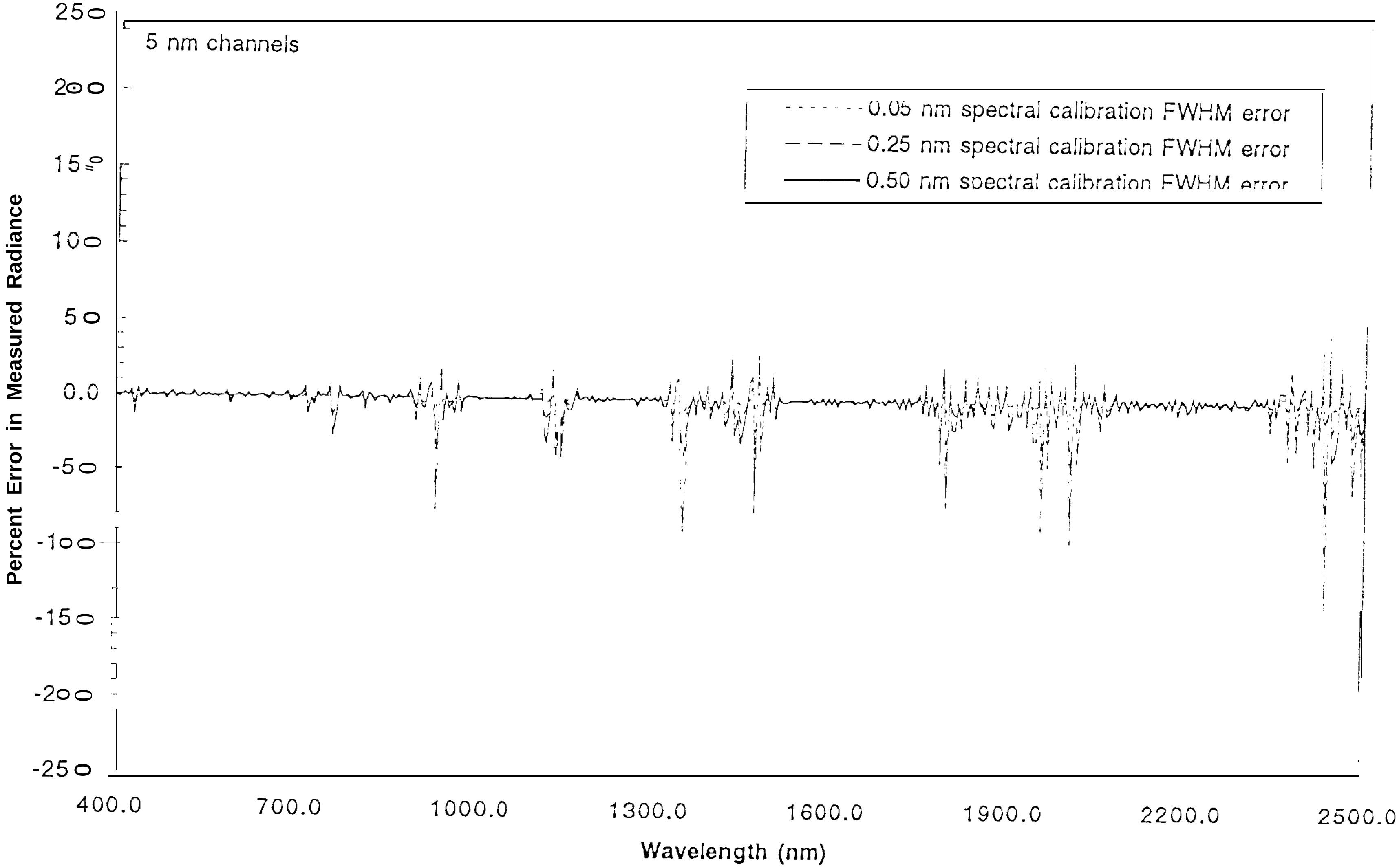
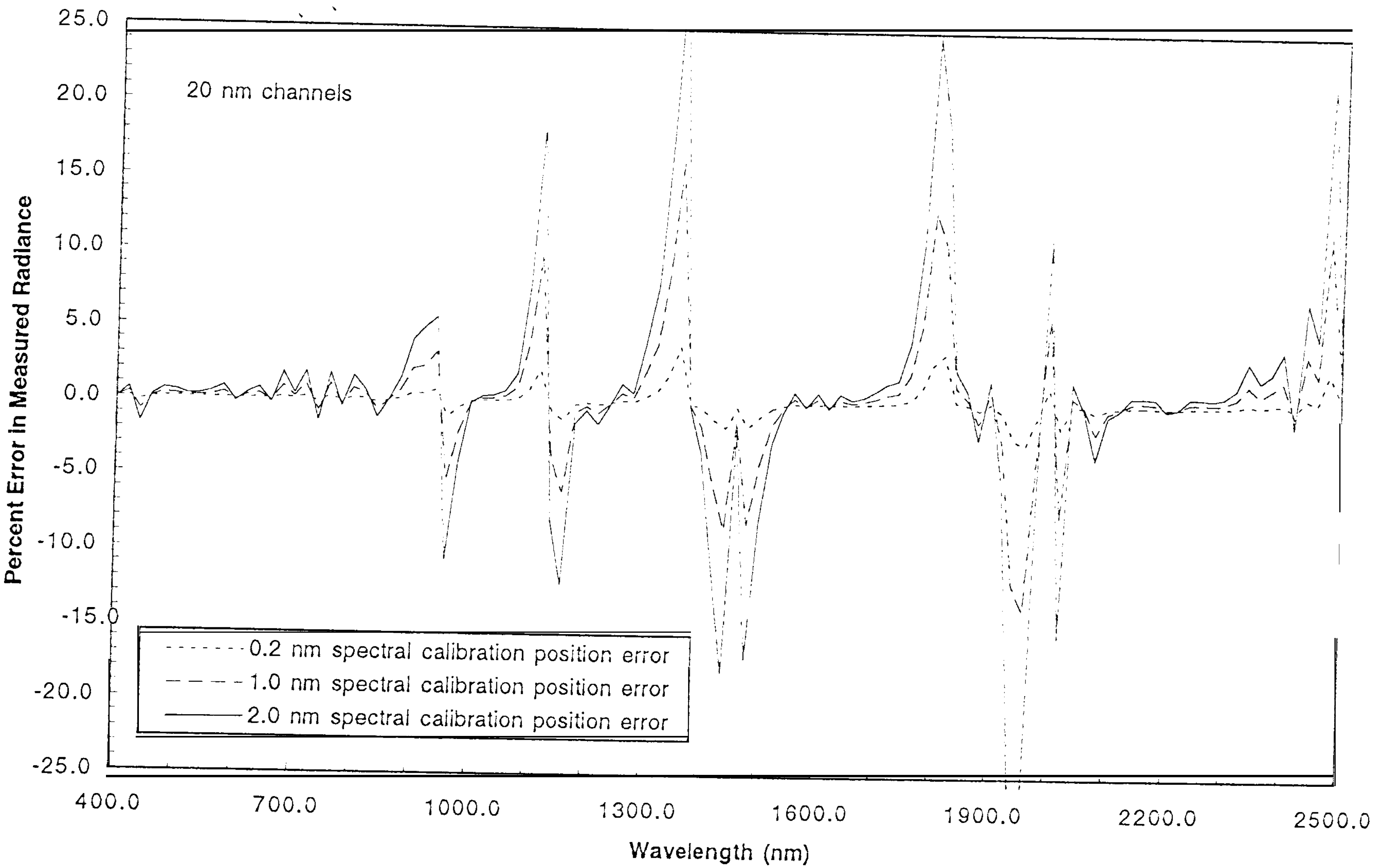

Percent Error In Measured Radiance
5 nm channels
0.05 nm spectral calibration position erro·
0.25 nm spectral calibration pos·tion erro.
0.50 nm spectral calibration position error
Wavelength (nm)

Fig 4a

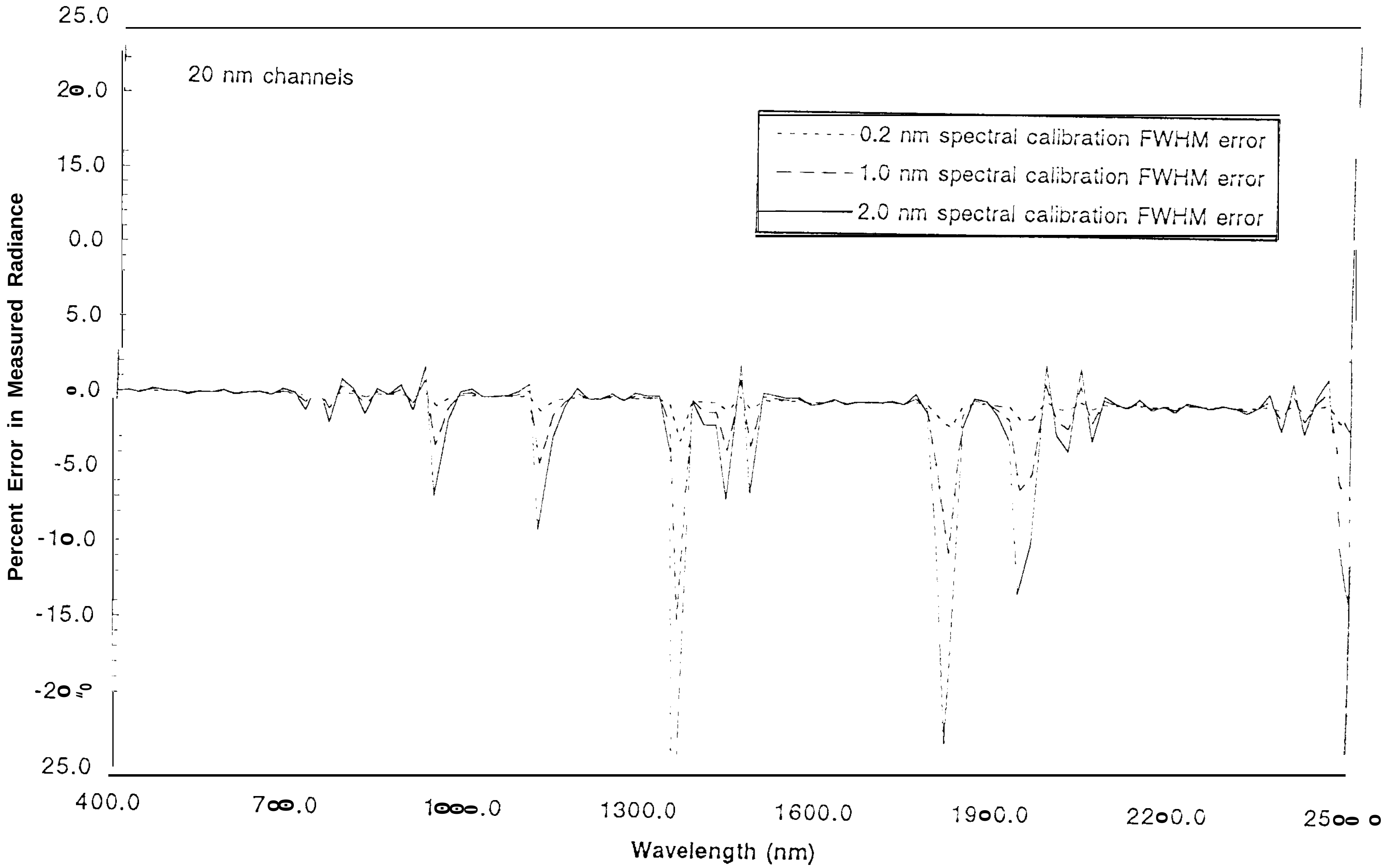


Percent Error in Measured Radiance
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
5 nm channels
0.05 nm spectral calibration FWHM error
0.25 nm spectral calibration FWHM error
0.50 nm spectral calibration FWHM error
400.0
700.0
1000.0
1300.0
1600.0
1900.0
2200.0
2500.0
Wavelength (nm)

Fig 4



20 nm channels
Percent Error in Measured Radiance
Wavelength (nm)
0.2 nm spectral calibration position error
1.0 nm spectral calibration position error
2.0 nm spectral calibration position error
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
400.0
700.0
1000.0
1300.0
1600.0
1900.0
2200.0
2500.0



25.0
20.0
15.0
0.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
25.0
Percent Error in Measured Radiance
20 nm channels
0.2 nm spectral calibration FWHM error
1.0 nm spectral calibration FWHM error
2.0 nm spectral calibration FWHM error
400.0
700.0
1000.0
1300.0
1600.0
1900.0
2200.0
2500.0
Wavelength (nm)

Fig 5